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Whitehead

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[54] LEVITATION SYSTEM WITH PERMANENT MAGNETS AND COILS

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[21] Appl. No.: 676,066

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[51] Int. Cl.[5] H02K 41/00; H02K 7/09; H02K 13/08

[52] U.S. Cl. 310/12; 310/90.5; 104/284

[58] Field of Search 310/12, 90.5, 13, 14; 104/284

[56] References Cited

U.S. PATENT DOCUMENTS

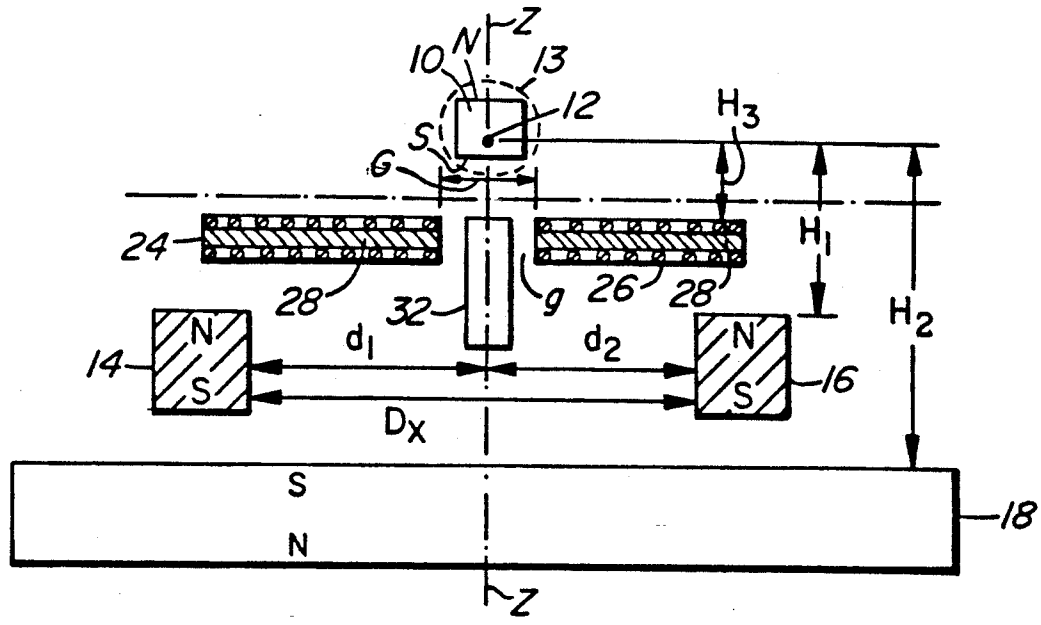
2,323,837	7/1943	Neal	35/46
3,512,852	5/1970	North	308/10
3,638,093	1/1972	Ross	318/687
3,815,963	6/1974	Wilk	308/10
3,888,553	6/1975	Wehde	308/10
4,040,681	8/1977	van der Heide	308/10
4,356,772	11/1982	van der Heide	104/282
4,382,245	5/1983	Harrigan	335/306
4,585,282	4/1986	Bosley	308/10
4,761,579	8/1988	Delassus	310/90.5
4,870,310	9/1989	Triplett	310/74
4,874,346	10/1989	Wachspress	446/484
4,910,633	3/1990	Quinn	361/144
4,975,669	12/1990	Wojtowicz	335/216
5,009,111	4/1991	West et al.	73/862.61

Primary Examiner—Steven L. Stephan
Assistant Examiner—D. R. Haszko
Attorney, Agent, or Firm—C. A. Rowley

[57] ABSTRACT

A levitation system for levitating a levitated magnetic element in a stable suspended position on one side of a separating plane using a magnetic arrangement on the opposite side of the separating plane. The magnetic arrangement provides a preselected static magnetic field configuration that interacts with a magnet in the levitated element so that the magnetic potential energy of this interaction increases for displacements of the element from its stable position in directions parallel to a stability plane and decreases for displacements of the element from the stable position perpendicular to the stability plane. Any movement perpendicular to the stability plane is sensed and used by a feedback control system to control a force applied to the levitated element to stabilize the element against displacement from the stable position in directions perpendicular to the stability plane.

29 Claims, 6 Drawing Sheets



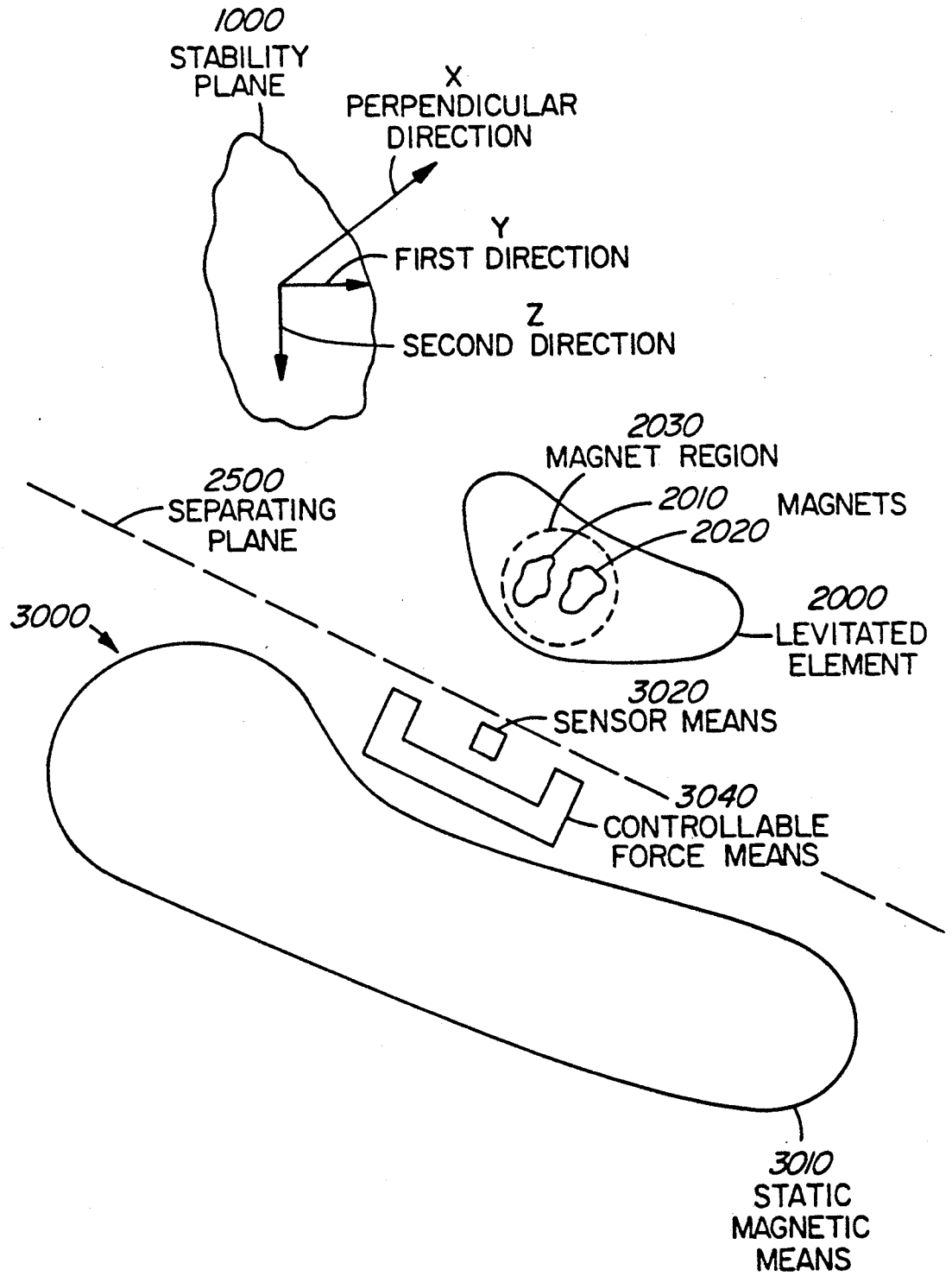

1000
STABILITY PLANE
X
PERPENDICULAR DIRECTION
Y
FIRST DIRECTION
Z
SECOND DIRECTION
2030
MAGNET REGION
2010
MAGNETS
2020
2500
SEPARATING PLANE
2000
LEVITATED ELEMENT
3000
3020
SENSOR MEANS
3040
CONTROLLABLE FORCE MEANS
3010
STATIC MAGNETIC MEANS

FIG. 1

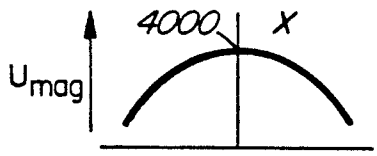


FIG. 2a

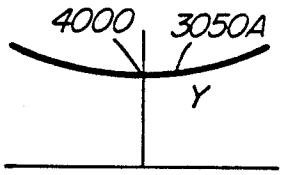


FIG. 2b

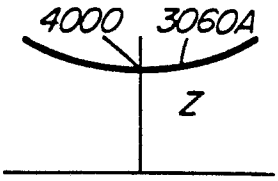


FIG. 2c

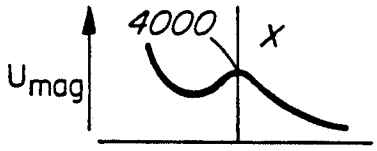


FIG. 3a

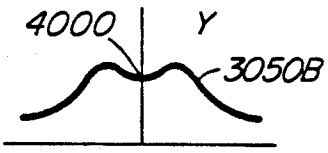


FIG. 3b

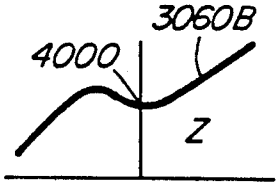


FIG. 3c

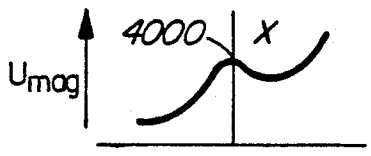


FIG. 4a

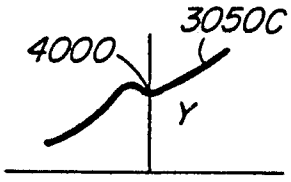


FIG. 4b

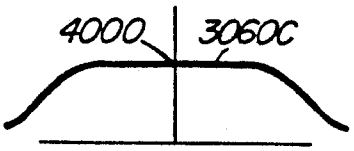
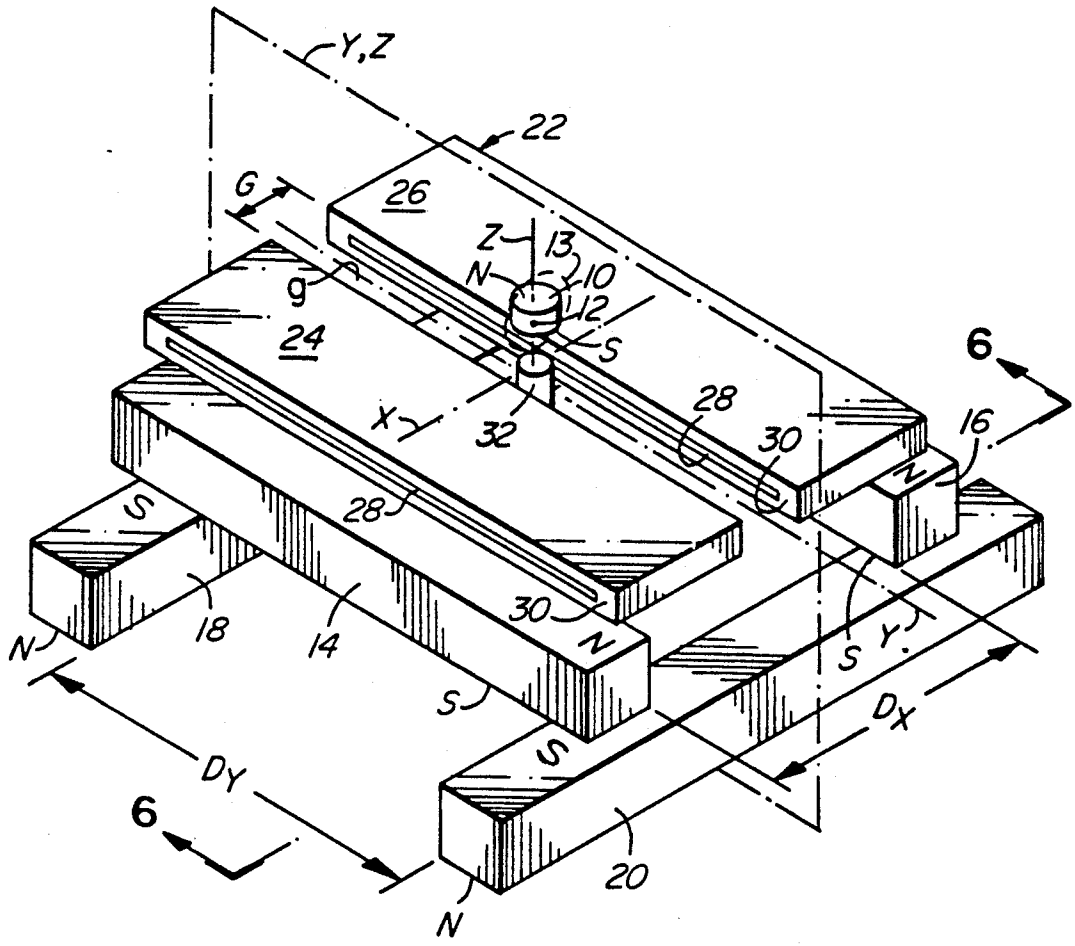


FIG. 4c


Y,Z
22
G
26
Z
13
N
10
12
g
24
S
6
X
32
28
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16
28
S
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18
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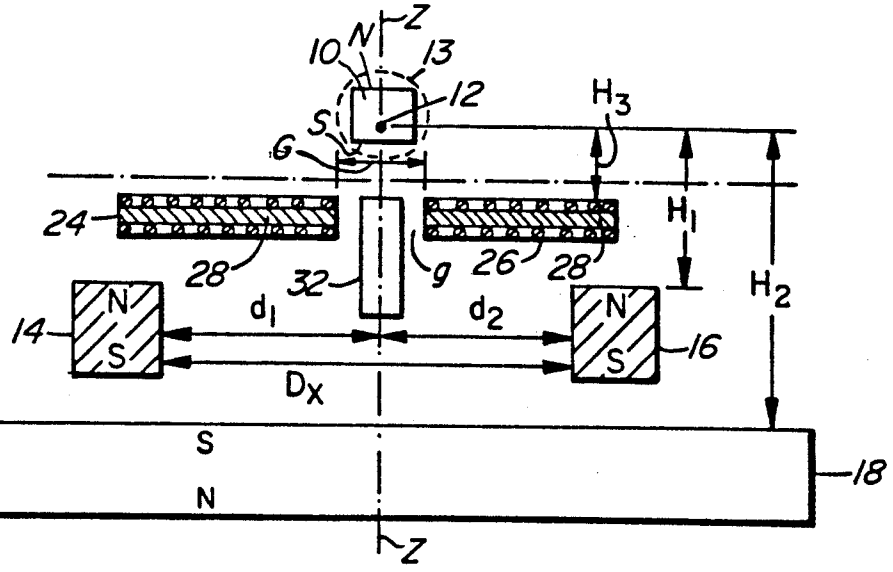
Y
S
S
D_X
D_Y
6
20
N

FIG. 5


Z
N
10
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H_3
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H_1
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g
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d_2
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16
D_X
S
N
18
Z

FIG. 6

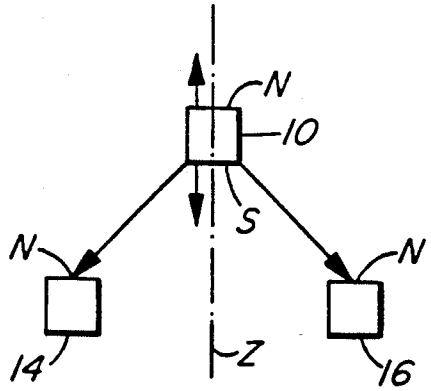


FIG. 7

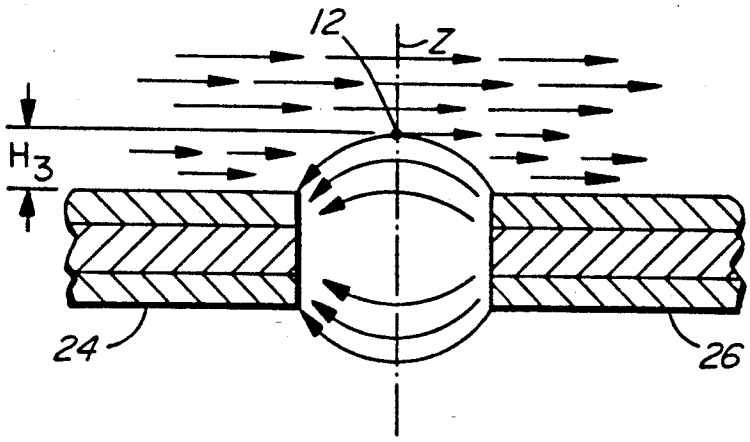


FIG. 8

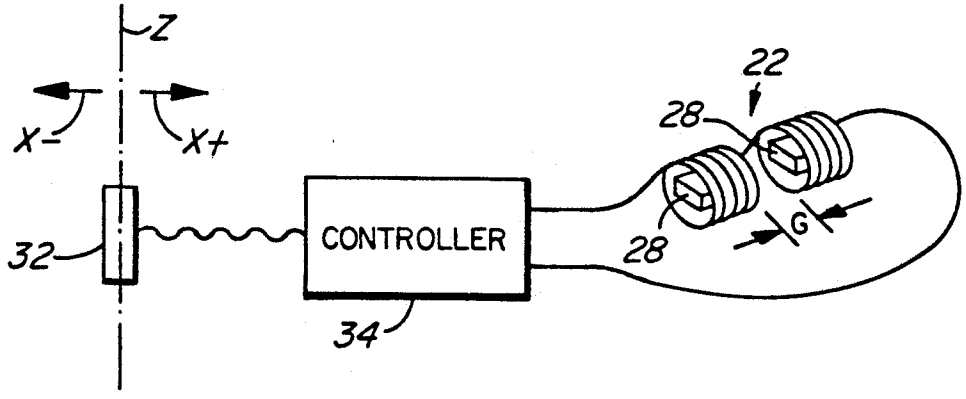


FIG. 9

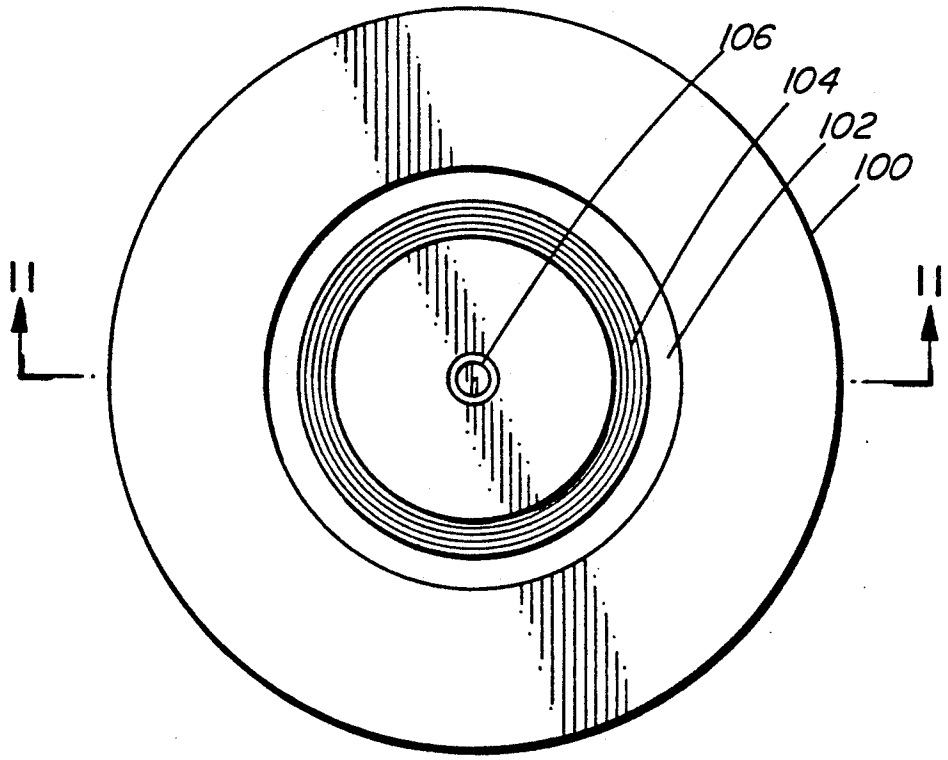


FIG. 10

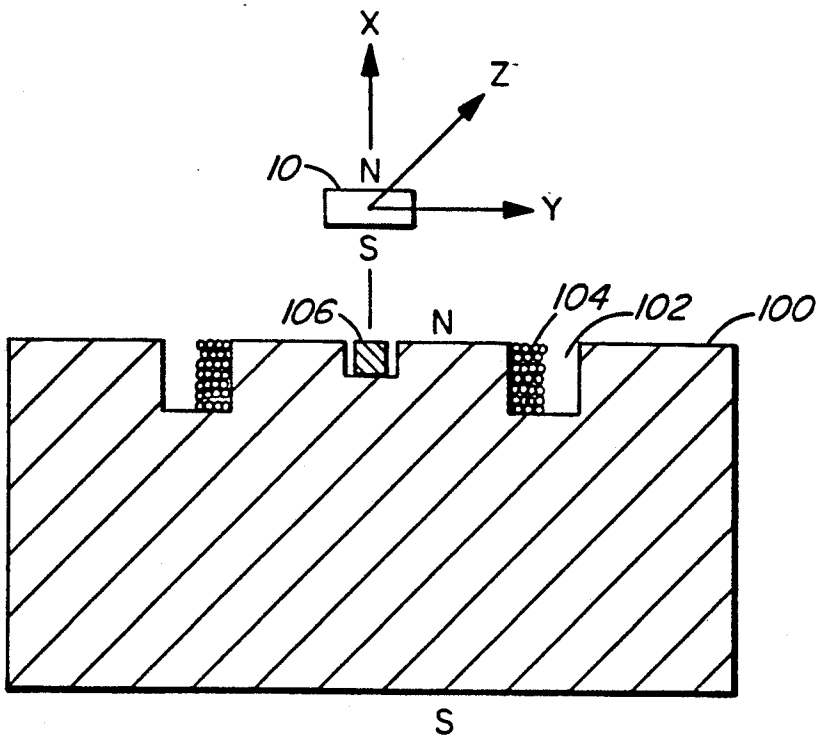


FIG. 11

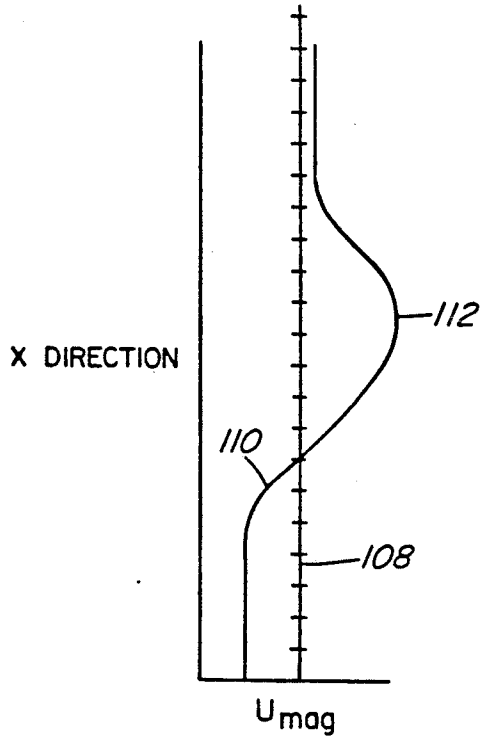

X DIRECTION
112
110
108
Umag

FIG. 12

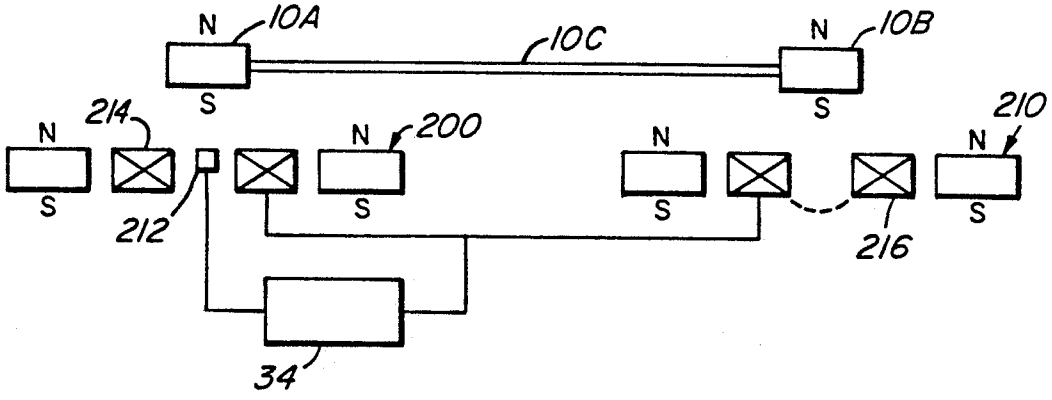

N
10A
10C
N
10B
S
S
214
N
200
N
210
N
S
S
S
S
212
216
34

FIG. 13

LEVITATION SYSTEM WITH PERMANENT MAGNETS AND COILS

FIELD OF THE INVENTION

The present invention relates to a levitation system. More particularly the present invention relates to a levitation system for holding a levitated magnetic element in stable levitated position on one side of a plane with the levitation device on the opposite side of the plane.

BACKGROUND OF THE PRESENT INVENTION

No effective system has been devised for maintaining a magnetic element at an equitable position by means of a magnetic field produced by any magnets positioned on one side of a plane, with the levitated element on the opposite side thereof and wherein external forces (e.g. gravity) tending to move the levitated element away from the levitating system are not essential for the equilibrium to exist.

Previous methods for low cost, stable magnetic levitation apply electromagnets mounted above the levitated magnetic element which is subjected to gravity. This configuration is able to provide stability in five degrees of freedom without a feedback control, and a simple feedback control is all that is required to stabilize the element in its vertical position. This system is not effective where an external force, e.g. gravity is not tending to move the element away from the electromagnets.

U.S. Pat. No. 2,323,837 issued Jul. 6, 1943 to Neal describes an attempt at levitating a magnetic element from below. In this arrangement a plurality of magnets are arranged in a circle and the levitated magnetic element is positioned within the circle with like poles of the circular and levitated magnets facing each other. This system has not proved satisfactory, as it is well established that such a system is inherently unstable.

U.S. Pat. No. 3,638,093 issued Jan. 25, 1972 to Ross describes a levitation system that functions also as a linear electromagnetic electric motor which supports the driven element above a track.

U.S. Pat. No. 4,585,282 issued Apr. 29, 1986 to Bosley shows a system for levitating a magnetic element from above with various feedback controls that may be employed to ensure stability of the levitated element. This patent also describes a possible technique for levitating an element and maintaining it in a stable position by means of levitating magnets positioned below a plane. This system has not proven satisfactory, possibly because the levitated object is unstable in two degrees of freedom, which makes feedback control for stabilization difficult.

BRIEF DESCRIPTION OF THE PRESENT INVENTION

It is an object of the present invention to provide a device for stable magnetic levitation of a magnetic object on one side of a plane by a magnetic levitation device on the opposite side of the plane permitting the use of simple, low cost components.

Broadly the present invention relates to a levitating system comprising a levitating device positioned on one side of a separating plane for maintaining a levitated element at a substantially stable position on the side of said separating plane remote from said one side and wherein said element includes magnetic means defining a magnetic region, and said device comprises a static magnet means producing a preselected static magnetic field configuration such that said element is levitated by said magnetic field configuration interacting with said magnetic region to cause the magnetic potential energy of said interaction to increase for substantially all displacements of said element from said stable position in directions parallel to a preselected stability plane and said magnetic potential energy to decrease for any displacement of said element from said stable position in a direction perpendicular to said stability plane, a sensor means generating a signal dependent on displacement of said element in said direction perpendicular to said stability plane, a controllable force means and a feedback control means, said feedback control means receiving said signal from said sensing means and controlling said controllable force means to stabilize said element against displacement from said stable position in said direction perpendicular to said stability plane.

Preferably said static magnetic means will comprise a first magnetic means which stabilizes said levitated element against displacement from said stable position parallel to a first direction within said stability plane and a second magnetic means which stabilizes said element against displacements parallel to a second direction within said stability plane and wherein said second direction is substantially perpendicular to said first direction.

Preferably said magnetic means forming said magnetic region will be formed by at least one magnet having a polarization substantially parallel to a preselected magnetic direction and wherein said magnetic region has a maximum dimension which is significantly less than the minimum distance between said magnets of said levitating device and said static magnetic means.

Preferably said stability plane will be substantially parallel to the direction from the center of the magnetic region to the center of the static magnetic means.

Preferably said first magnetic means and said magnetic element will have their opposite magnetic poles closest to each other.

Preferably said first magnetic means will comprise a pair of spaced bar magnets with their poles facing parallel to the direction from the center of said pair of magnets toward the center of the magnetic region.

Preferably said second magnetic means will comprise a second pair of spaced bar magnets with poles facing in substantially the opposite direction as the poles of said first magnetic means.

Preferably said controllable magnetic means will comprise an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field, said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field generated by said coils in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable point of suspension.

Preferably said sensor means will comprise a Hall effect sensor sensing said movement of said element in said direction perpendicular to said stability plane.

BRIEF DESCRIPTION OF THE DRAWINGS

Further features, objects, and advantages will be evident from the following detailed description of the

preferred embodiments of the present invention taken in conjunction with the accompanying drawings in which:

FIG. **1** is a schematic illustration of the general concept of the present invention.

FIGS. **2***a–c*, **3***a–c* and **4***a–c* provide three independent examples of graphs of U_{mag} (magnetic potential energy) of the interaction of the magnetic region of the levitated element with the magnetic field from the static magnetic means versus displacement in a direction perpendicular to the stability plane, (a), or in mutually perpendicular directions parallel to the stability plane, (b), and (c).

FIG. **5** is an isometric view of one form of the present invention showing the operating elements.

FIG. **6** is a section along the line **6—6** (x axis) of FIG. **5**.

FIG. **7** is a schematic illustration of the levitation system of the present invention for maintaining a substantially constant spacing in the z direction.

FIG. **8** is a schematic representation of the x direction control electro magnet.

FIG. **9** is a schematic illustration of the control system for the electromagnet.

FIG. **10** is a plan view of a single levitating magnet in a system incorporating the present invention.

FIG. **11** is an enlarged cross section through the magnet of FIG. **10** showing a magnetic element levitated thereabove.

FIG. **12** is a curve of magnetic potential energy U_{mag} versus distance from the face of the magnet showing an ordinary magnet and a magnet provided with an annular groove as illustrated in FIGS. **10** and **11**.

FIG. **13** shows a further embodiment of the present invention levitating a pair of rigidly coupled levitated elements.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Unlike most other large gap magnetic levitation devices the force of gravity is not a key part of the operation of the present invention but is simply an example of an external force which may perturb the levitated element from a stable position by a small distance. In principle the device of the present invention may be turned to any angle relative to gravity and the levitated element will stay in a stable position relative to the levitating device, provided the device is constructed with sufficient stability in all directions.

Obviously in most instances with the notable exception of a free fall condition in outer space, gravity will play a role and the strength of the stability has to be strong enough to resist gravity. For any geometrical design, this will be true at a certain size or scale since the smaller the size the stronger the magnetic stability forces will be compared to gravity. The characteristics of a good design constructed in accordance with the present invention will be its capability to withstand gravity at comparatively large size scale, that it would require only comparatively small amount of magnetic material, and that it be comparatively easy to manufacture.

The levitated element may change orientation somewhat when displaced so that not every point moves the same amount in the same direction but nevertheless the element will remain stable relative to the magnetic levitating device.

In order to describe the motion of the element, it is therefore important to define an effective magnetic center as a reference point to define such displacement. This can be done as follows.

The magnetic dipole density distribution of the magnets in the levitated element, which define the magnetic region of the levitated element, may be described when the element is at the stable position and orientation, by a magnetic dipole moment density D(x,y,z) where x,y and z are the coordinates relative to an arbitrary set of mutually perpendicular axes. Using this definition, the magnetic center of the levitated element is designated to be at the x_0, y_0, z_0 point given by the formula

$$x_o = \frac{\int dxdydzxD^2(x.\ y.\ z)}{\int dxdydzD^2(x.\ y.\ z)}$$

$$y_o = \frac{\int dxdydzyD^2(x.\ y.\ z)}{\int dxdydzD^2(x.\ y.\ z)}$$

$$z_o = \frac{\int dxdydzzD^2(x.\ y.\ z)}{\int dxdydzD^2(x.\ y.\ z)}$$

and the point (x_0, y_0, z_0) is the equilibrium position for the element. If the element is displacement from the equilibrium position, the magnetic center, as defined above, will move to new coordinates (x_{mc}, y_{mc}, z_{mc}), and the displacement of the element can be uniquely described by the vector (x_{mc}-x_0, y_{mc}-y_0, z_{mc}-z_0).

In any new position x_{mc}, y_{mc}, z_{mc} for the effective magnetic center there will be a stable orientation of the levitated element which may not be exactly the same as for the original position of the effective magnetic center. For the new position there will be a new, different magnetic dipole density distribution

$$\bar{D}(x_{mc}, y_{mc}, z_{mc}, x,y,z) \tag{2}$$

Additionally, the static magnetic potential energy U_{mag} for this particular position for the levitated element is given by

$$U_{mag}(x_{mc}, y_{mc}, z_{mc}) = -\int dxdydz\bar{D}(x_{mc}, y_{mc}, z_{mc}, x,y,z).\bar{B}_s(x,y,z) + C \tag{3}$$

where $B_s(x,y,z)$ = static magnetic field, and C is an arbitrary constant. Magnetic potential energy, like any potential energy, provides a measure of stability or instability about an equilibrium point and more specifically the force F at any point is given by

$$\bar{F}(x_{mc}, y_{mc}, z_{mc}) = -\nabla U_{mag}(x_{mc}, y_{mc}, z_{mc})$$

i.e. the force is toward the place or location of lower potential energy and the faster the potential energy changes with position the greater the force. Because of this relationship, it is helpful to describe the nature of equilibria by the manner in which U_{mag} varies spatially in the region around the equilibrium point.

Although the above description is sufficient for understanding the technical terms of this invention, it may help to put this invention in context to consider in more detail the implications of physical laws of magnetic fields with regard to levitation systems. In that regard, what follows is a brief summary of the scientific background of this invention.

In practical magnetic levitation systems of the types considered here, the levitated object may include one small magnetic dipole, or an array of such magnetic dipoles rigidly connected to one another. The mathe-

matical description of the possible effects of permanent magnetic fields near an equilibrium point (i.e. a stable position 4000 and orientation for the levitated object for which there is no net force or torque), will be treated first for the case of the single point dipole, and then generalized to the multiple-dipole.

A levitated dipole has six degrees of freedom-three of position and three of orientation. However, the treatment can be simplified by assuming that at equilibrium, the levitated dipole, having magnetic dipole moment $\vec{D}$, is parallel to the magnetic field, i.e.

$$\vec{D}\times\vec{B}=0 \tag{4}$$

because this is the orientation of minimum potential energy. If $\vec{B}_s(x,y,z)$ represents the magnetic field from the static magnetic means as a function of position, then (4) implies that the magnetic potential energy of the point dipole, as a function of position is given by

$$U_{mag}(x,y,z)=-DB(x,y,z)+C \tag{5}$$

where C is an arbitrary constant. With no loss of generality, we will assume that at the equilibrium point, $x=y=z=0$.

In considering matters of stable and unstable equilibria, it is appropriate to expand the magnetic potential energy function $U_{mag}(x,y,z)$ into 0th, 1st, and 2nd order terms of displacement about the equilibrium point (i.e. terms in 0th power, 1st power, and 2nd power in the spatial variables x,y, and z). The 0th order term represents the potential energy at the equilibrium point, the first order terms correspond to magnetic forces at the equilibrium point (which can be used to counteract externally applied forces such as gravity, to create the equilibrium condition) and the second order terms correspond to stabilizing/destabilizing forces which are zero at the equilibrium point, but increase in proportion to the displacement from the equilibrium position.

The range of possible permanent magnetic fields is restricted by the Maxwell Equations, which in free space and at steady state imply the condition that

$$\nabla\times\vec{B}=0 \text{ and } \nabla.\vec{B}=0 \tag{6}$$

This condition, coupled with the definition of U_{mag} in (5) above, significantly restricts the allowable second order terms in the expansion of U_{mag} about the equilibrium point. In particular, a term of the form

$$U_{mag}=K(x^2+y^2+z^2)$$

where K is a positive constant, which would correspond to a field which is stabilizing (i.e. providing a restoring force toward equilibrium) in all three dimensions, is not possible. This is why stable equilibrium in a static field alone is not possible. On the other hand, equation (6) places no restriction on the 0th and 1st order terms.

The following equation represents the most general 2nd order expansion of $U_{mag}(x,y,z)$, subject to (6):

$$U_{mag}(x,y,z) = U_o + (G_x)x + (G_y)y + (G_z)z + (P_{xy})xy + (P_{xz})xz + (P_{yz})yz + (S_{xy})[x^2 - y2] + (S_{xz})[x^2 - z^2] + (S_{yz})[y^2 - z^2] \tag{7}$$

The constants Gx, Gy and Gz (gradient coefficients) represent magnetic force in the x,y,z directions, and the second order coefficients Pxy, Pxz, Pyz, ("product") and Sxy, Sxz, Syz ("square") represent stabilizing forces in some directions, but destabilizing forces in other directions. (It should be noted, that the last term, with coefficient Syz, is not really necessary, as this term can be duplicated by a positive value for Sxz and the opposite value for Sxy. While the term is not necessary, it is kept in as it simplifies the terminology in this Cartesian coordinate depiction).

Although the situation is more complex for the multiple dipole case, a generalization to this case is possible, with very simple results. Since in this case the levitated object has a substantial physical extent, it is simplest to let the coordinates x, y, z refer to the location of the effective magnetic center of the levitated object, as defined in 1. Again, it is assumed that we are interested in the situation in the immediate vicinity of an equilibrium point, and that the orientation of the object, for any given location x, y, z will be that of minimum potential energy. With these generalizations, the function $U_{mag}(x,y,z)$ is completely determined for any given magnetic field, but its functional form will be much more complex than that of (5), because it will depend on the strengths, relative positions, and relative orientations of the various component dipoles.

Fortunately, despite the complexity in the functional dependence of $U_{mag}(x,y,z)$ on $\vec{B}(x,y,z)$, the net effect of restriction (6) is precisely the same as the point dipole case, namely that the most general second-order expansion about the equilibrium position is given by (7).

The main difference between the two cases arises in the design of specific magnetic fields required to achieve specific values for the coefficients in (7). In the point dipole case, the fields themselves can be very simply determined, by means of equation (5) whereas the situation is understandably more complex in the multiple dipole case.

Given that the allowable second order terms cannot provide overall stability, it is clear that stability can only be achieved by sensing the position of the levitated object, and adjusting the first order (gradient) terms in response, so as to actively direct the object back toward the desired equilibrium position. Indeed, since the second order terms are all destabilizing in some directions, it might seem preferable to design a magnetic field resulting in just 0th and 1st order terms—something which is readily achievable with well known magnet designs.

As a practical manner, such an approach would be exceedingly difficult. The reason for this is that such feedback control would require sensing and reacting to three dimensional degrees of freedom, for which the resulting responses will not be generally independent. Particularly because a levitated object has very little natural damping, and because the inductive nature of electromagnets introduces phase lags in their response to control signals, achieving stability for such a complex control system will be very difficult and expensive. Indeed, achieving good stability with even one channel of active control is often difficult with magnetic levitation.

The reason that the second order terms in (7) are in fact useful is that they allow the creation of a permanent field in which the levitated object is stable in two of the three physical dimensions, and unstable in only one, thus tremendously simplifying the active control requirements as described above. Three examples of coef-

ficients for second order terms which achieve this effect are:

Example	P_{xy}	P_{xz}	P_{yz}	S_{xy}	S_{xz}	S_{yz}	NOTE
1	0	0	0	−1	−1	0	unstable in x direction
2	0	0	0	1	0	−1	unstable in y direction
3	0	0	0	0	1	1	unstable in z direction

Thus is can be seen that from a scientific viewpoint, it is possible to create a static magnetic field yielding an equilibrium condition which is stable in two directions defining a plane of stability, and unstable in only the direction perpendicular to the plane of stability. Taken in this context, the invention described herein provides a system employing such a stability type, wherein the required field is created by a static magnetic means positioned entirely on the side of a reference plane opposite the location of the equilibrium point itself. All of this will be made clearer in the following detailed description of the drawings.

DETAILED DESCRIPTION OF DRAWINGS

Referring to FIG. **1** which provides the most general illustration of the present invention, a stability plane **1000** has been shown in space and a preselected first direction and its respective direction perpendicular thereto designated as a second direction have been indicated by the letters y and z. The direction perpendicular to the stability plane has been labelled the perpendicular direction x.

The levitated element has been schematically depicted at **2000** and includes generally permanent magnets **2010** and **2020** (two have been shown but more or fewer magnets may be used to define a magnetic region **2030**).

On the opposite side of separation plane **2500** is levitating device **3,000** provided by a static magnetic means **3010**, a sensor **3020** and a controllable force generating means **3040**.

Generally the static magnetic device **3000** will generate a magnetic field configuration that interacts with the magnets **2010** and **2020** of the levitated element **2000** so that movement of the magnetic region **2030** parallel to the stability plane **1000**, i.e. in the y and z directions as depicted by graphs (b) and (c) will result in increased magnetic potential energy U_{mag} as shown by the curves **3050A**, **3050B**, **3050C**, **3060A**, **3060B** and **3060C** in FIGS. **2**, **3** and **4** which show the potential energy increasing on opposite sides of the stability position **4000** for the y and z mutually perpendicular directions.

Graphs (a) of FIGS. **2**, **3** and **4** show the instability in the x direction wherein the magnetic potential energy decreases with any movement in the x direction regardless of direction i.e. away from the stability position **4000** in directions perpendicular to the stability plane **1000**.

It will be evident that to generate this type of magnetic configuration, having its potential energy increase with movement in two substantially perpendicular directions parallel to a stability plane and decrease in movements perpendicular to the stability plane, it is possible to use a large variety of different static magnetic means which can be designed by employing the well known laws of magnetic fields.

The following provides several examples of magnetic devices suitable for carrying out the present invention.

In the illustrated arrangement shown in FIG. **5** the levitated element **10** is positioned on the z axis at a stable point or position of suspension **12** (i.e. position **4000** described above) on the z axis and is held at this point against relative movement in the x direction parallel to the x axis or in the y direction parallel to the y axis or in the z direction parallel to the z axis as will be described more fully hereinbelow. The y and z axes define the stability plane y, z which has been illustrated as a vertical plane with the z axis vertical. The x and y axes are mutually perpendicular to the z axis.

The first magnetic means in the arrangement illustrated in FIG. **5** is composed of a first pair of bar magnets **14** and **16** which have been positioned substantially parallel to the y axis and spaced on opposite sides of the stability plane y,z extending as above indicated in the y and z directions and indicated by dot dash lines in FIG. **5** i.e. spaced in the x direction and symmetric relative to the stabilization plane y,z. In this case the two magnets **14** and **16** are essentially the same and have essentially the same strength. The spacing D_x between the magnets **14** and **16** is bisected by the plane y,z. The length of these magnets **14** and **16** in the y direction and their extension on opposite sides of the stabilization point **12** are sufficiently to appear almost infinitely long relative to the magnetic region schematically indicated by the dash line **13** around the element **10**. The element **10** is suspended with the magnetic center of the magnetic region **13** of the element **10** substantially positioned at the stable suspension point **12**.

The polarity of the magnets **14** and **16** is arranged so that the magnetic poles of the magnets face in the z direction. In the illustrated arrangement the north pole has been directed upward, the south pole downward as indicated by the letters N and S on these magnets **14** and **16**.

The levitated magnetic element **10** has its magnetic poles also arranged facing in the z directions but is positioned with its magnetic poles arranged in opposition to those of magnets **14** and **16** so that in the illustrated arrangement the upwardly facing pole is a north pole (N) and a downwardly facing pole is a south pole (S), i.e. opposite poles are closer to each other between the magnetic element **10** and the magnets **14** and **16** of the first magnetic means.

These magnets **14** and **16** stabilize the element from movement in the z direction, while providing a destabilizing effect in the x direction, and a neutral effect in the y direction.

The second magnetic means is formed by a second pair of bar magnets **18** and **20** which in the illustrated arrangement are positioned below the magnets **14** and **16**, i.e. spaced farther in the z direction from the point **12** than the magnets **14** and **16**. These magnets **18** and **20** have their longitudinal axis substantially parallel to the x axis, i.e. substantially perpendicular to the axis of the magnets **14** and **16** and are arranged with their magnetic poles facing in the z direction but inverted relative to magnets **14**, **16** and **10** so that in illustrated arrangement the south poles (S) of the magnets **18** and **20** face vertically upward and the north poles (N) downward.

The spacing between the two magnets **18** and **20** has been indicated by the distance D_y and assuming that the magnets **18** and **20** are of the same strength they will also be positioned symmetrical relative to the axis z, i.e.

will be equally spaced from the vertical axis z on which the point **12** is located.

These magnets **18** and **20** stabilize the element **10** from movement in the y direction while providing a destabilizing effect in the z direction, and a neutral effect in the x direction. It is therefore important that the magnetic forces applied to the element **10** by the magnets **18** and **20** be significantly less than the forces applied by the magnets **14** and **16** of the first magnetic means, so that stability in the z direction is not lost.

Thus the first and second magnet means formed by the magnets **14** and **16** and **18** and **20** respectively stabilize the element **10** from movement in the plane y, z while creating a destabilizing effect in the x direction.

Movement in the x direction must be overcome by a feedback control. In the illustrated arrangement the controllable force means is a controllable magnet formed by a split coil **22** having a first coil section **24** and second coil section **26**, axially spaced to form a gap g therebetween, the gap having a substantially constant width G measured in the x direction, the gap g being centered on and parallel to the plane y, z in which the point **12** is located.

The coil sections **24** and **26** are each formed by a core **28** with windings in series and wound there around in the same direction, the windings being contained in the coil section **30** surrounding each of the cores **28** as will be described hereinbelow.

A suitable sensor which may for example take the form of a Hall effect sensor provided, as indicated at **32** positioned on the z axis in which the point **12** is located, is adapted to sense any movement of the element **10** in the x direction. The sensor **32** sends a signal to a feedback control controlling the split coil **22** to maintain the element **10** properly positioned relative to the locating plane y, z. The sensor **32** sends a signal to the controller **34** which may be positioned in any convenient location (see FIG. **9**) if the element **10** moves in either of the two opposite x directions and the controller **34** directs electrical current to the split coil electromagnet **22** to apply a magnetic force to the element **10** to move the element **10** back into the plane y, z if for some reason the element should tend to move therefrom. Care must be taken in designing the controller to ensure that oscillations about the equilibrium are damped rather than increasing exponentially using a variety of techniques well known in the art of magnetic levitation and servo control design.

The heights H_1, H_2 and H_3 as illustrated in FIG. **6** are respectively, the heights measured in the z direction from the stabilized point **12** to the magnets **14** and **16**; to the magnets **18** and **20**; and to the coil magnet **22**.

In building the device preferably the two bar magnets **14** and **16** will be substantially identical. The spacing D_x will be such that with no other magnets in position the height H_1 will be a maximum. This can be accomplished by, for example, placing the magnetic element **10** to be levitated within a tube so that there can be no movement in the x or y direction, but permitting substantially free movement in the z direction and gradually separating the magnets **14** and **16** to find the spacing D_x that will result in a maximum for height H_1. The magnets **14** and **16** are then mounted and the spacing of the location of the point **12** in the z direction is determined.

The element **10** must be stabilized in the y direction without significantly changing the position of the point **12** in the z direction. This is accomplished by positioning the magnets **18** and **20** at a selected spacing D_y and at a height from the point **12** H_2 wherein stabilization in the y direction is obtained and the spacing H_1 is not disturbed. The spacing D_y and H_2 will vary depending on the strengths of the magnets **18** and **20**. In the illustrated arrangement the magnets **18** and **20** are essentially the same strength as the magnets **14** and **16** and $H_2 \cong 2H_1$ has been found satisfactory for a spacing $D_y \cong 2D_x$.

The height H_3 is determined, as shown in FIG. **8**, to be the height above the top surfaces of coils **24** and **26** at which the leakage flux from the gap G cancels the surrounding field from these coils. At this point, the only effect of the field configuration from these coils on magnet **10** will be a force in the x direction proportional to the current flowing in these coils.

The above example has dealt with substantially straight magnetic elements forming a first and second magnetic means generating in conjunction with the element **10** the required magnetic potential energy distribution to stabilize the element **10** in the y,z stabilization plane, and the use of a controlled leakage magnetic field to stabilize the element against movement out of the plane y,z.

FIGS. **10**, **11** and **12** illustrate a different system utilizing a single magnetic element to stabilize the levitated element **10** in a stabilization or locating plane y,z parallel to the face of the magnet illustrated in FIG. **11** with x axis perpendicular to the y,z plane and to the face of the permanent magnet **100**. The orientation of the axes, or naming of the axes as x, y or z axes has no significance, however for consistency y and z axis have been used to define a locating plane or the plane of stabilization y,z established by a permanent magnet means of the levitation device in both embodiments.

In the embodiment currently being described the permanent magnet **100** is substantially cylindrical as illustrated in FIG. **10** and is provided with an annular groove **102** concentric to the x axis and in which is received a coil **104** that forms the controllable force means, i.e. the controllable magnet that is operated to control the position of the element **10** in the x direction. Also positioned within the magnet **100** on the axis x is a sensor **106** which senses the position of the element **10** relative to the face of the magnet, i.e. the spacing in the x direction. The sensor **106** may be any suitable sensor such as a Hall sensor and functions to provide a signal as described above with respect to the sensor **32**.

The position and size of the annular groove **100** is a key feature in forming the levitation system illustrated in FIGS. **10**, **11** and **12**. A graph magnetic potential energy U_{mag} versus distance in the x direction is shown in FIG. **12**. The hash line **108** indicates the typical magnetic effect generated by the magnet **100** when no groove **102** is provided. The curve **110** illustrates the changed magnetic potential energy when groove **102** is provided. It will be noted that the magnetic potential energy when the groove **102** is provided reaches a maximum at the point **112**, at a distance from the surface of the magnet **100** determined by the strength of the magnetic **100** and the size and position of the groove **102**. This point of maximum magnetic potential energy **112** indicates that the magnetic potential energy decreases on opposite sides of the point **112** so that the element **10** positioned at this point is unstable in the x direction, however in both the y and z directions, i.e. in the y,z plane the magnetic potential energy must increase in substantially all directions of displacement so there is stability in the y,z plane. However, as above indicated,

stability in the x direction, i.e. perpendicular to the y,z plane, is not provided by the main magnet **100**.

To obtain stability in the x direction, the sensor **106** senses the position of the element **10** and a feed back controller such as the controller **30** is suitably programmed to adjust the current in the coil **104** to hold the element **10** in stable position, i.e. at a fixed distance from the magnet **100** measured in the x direction.

In the FIG. **5** embodiment the stability plane y,x is substantially parallel to a straight line (z axis) between center of the static magnetic means (magnets **14**, **16**, **18** and **20**) and the center of the magnetic region **13** of the levitated element **10**, while in the FIGS. **10** and **11** embodiment the stabilizing plane y,z is perpendicular to the straight line (z axis) connecting the center of the static magnet means **100** with the center magnetic region **13** of the levitated element **10**.

The above examples have all used a levitated element which has been shown as having a single magnetic element. It is also possible to utilize the present invention as shown in FIG. **13** to support two rigidly interconnected elements **10A** and **10B**, interconnected for example by a bar or the like **11**, in levitated position relative to a levitation device by providing a magnetic arrangement for each discrete magnetic element **10A** or **10B**, i.e. the magnetic devices **200** and **210** shown in FIG. **9**. In the arrangement illustrated a sensor **212** senses the position of one of the levitated magnetic elements, in this case, the magnetic element **10A**, controls the controller **34** to adjust suitable coils **214** to stabilize the magnetic element **10A** and a similar coil **216** to stabilize the element **10B** from movement.

It will be apparent that in some cases it may be satisfactory to eliminate one of the coils **214** or **216**.

The above specific examples do not depend on gravity, and, it will be apparent that if the element **10** is subject to different gravitational or other external forces that are not too great, the element **10** will simply be positioned slightly differently relative to the levitation means. It will also be evident that the levitation and orientation of the levitated element **10** will be influenced by the mass distribution of the whole entity being levitated.

As mentioned earlier, the stability plane need not necessarily be horizontal or vertical, nor parallel or perpendicular to the line between the center of the static magnetic means and the center of the levitated element. While Hall effect sensors have been described hereinabove, other sensor means may be used, for example, detectors employing reflected light or ultrasonic sound waves, capacitive sensors using electrostatic effects or as another example, detection of the force created by the field from the levitated element acting on the static magnetic means.

Similarly the controllable force means to maintain the element in the stability plane, i.e. the y,z plane, has been disclosed as controllable magnetic means but presumably they could also include means employing controlled forced air, electrostatic forces, magnetic forces from a variable magnet or magnetic forces controlled by small controlled displacement of the static magnetic means (effective inertial forces) as well as other satisfactory non-contacting force applying means.

Having described the invention, modifications will be evident to those skilled in the art without departing from the spirit of the invention as defined in the appended claims.

I claim:

1. A levitating system comprising a levitating device positioned on one side of a separating plane for maintaining a levitated element at a substantially stable position on the side of said separating plane remote from said one side and wherein said levitated element includes magnetic means defining a magnetic region, and said levitating device comprises a static magnetic means producing a preselected static magnetic field configuration such that said levitated element is levitated by said magnetic field configuration interacting with said magnetic region to cause magnetic potential energy of said interaction to increase for substantially all displacements of said levitated element from said stable position in directions parallel to a preselected stability plane and said magnetic potential energy to decrease for any displacement of said levitated element from said stable position in a direction perpendicular to said stability plane, a sensor means generating a signal dependent on displacement of said levitated element in said direction perpendicular to said stability plane, a non contacting controllable force means and a feedback control means, said feedback control means receiving said signal from said sensor means and controlling said controllable force means to stabilize said levitated element against displacement from said stable position in said direction perpendicular to said stability plane.

2. A levitating system as defined in claim **1** wherein said static magnetic means comprises a first magnetic means which stabilizes said levitated element against displacement from said stable position parallel to a first direction within said stability plane and a second magnetic means which stabilizes said levitated element against displacements parallel to a second direction within said stability plane and wherein said second direction is substantially perpendicular to said first direction.

3. A levitating system as defined in claim **1** wherein said magnetic means forming said magnetic region is formed by at least one magnet having a polarization substantially parallel to a preselected magnetic direction and wherein said magnetic region has a maximum dimension which is significantly less than the minimum distance between said at least one magnet and said static magnetic means.

4. A levitating system as defined in claim **1** wherein said stability plane is substantially parallel to a straight line between the center of said static magnetic means and the center of said magnetic region.

5. A levitating system as defined in claim **3** wherein said static magnetic means comprises a first magnetic means which stabilizes said levitated element against displacement from said stable position parallel to a first direction within said stability plane and a second magnetic means which stabilizes said levitated element against displacements parallel to a second direction within said stability plane and wherein said second direction is substantially perpendicular to said first direction.

6. A levitating system as defined in claim **4** wherein said static magnetic means comprises a first magnetic means which stabilizes said levitated element against displacement from said stable position parallel to a first direction within said stability plane and a second magnetic means which stabilizes said levitated element against displacements parallel to a second direction within said stability plane and wherein said second direction is substantially perpendicular to said first direction.

7. A levitating system as defined in claim 4 wherein said magnetic means forming said magnetic region is formed by at least one magnet having a polarization substantially parallel to a preselected magnetic direction and wherein said magnetic region has a maximum dimension which is significantly less than the minimum distance between said at least one magnet and said static magnetic means.

8. A levitating system as defined in claim 5 wherein said stability plane is substantially parallel to a straight line between the center of said static magnetic means and the center of said magnetic region.

9. A levitating system as defined in claim 2 wherein said first magnetic means comprises a pair of spaced bar magnets with their poles facing in a direction parallel to a straight line from the center of said pair of magnets to the center of said magnetic region of said levitated element and wherein said first magnetic means and said magnetic element have their opposite magnetic poles adjacent to each other.

10. A levitating system as defined in claim 6 wherein said first magnetic means comprises a pair of spaced bar magnets with their poles facing in a direction parallel to a straight line from the center of said pair of magnets to the center of said magnetic region of said levitated element and wherein said first magnetic means and said magnetic element have their opposite magnetic poles adjacent to each other.

11. A levitating system as defined in claim 8 wherein said first magnetic means comprises a pair of spaced bar magnets with their poles facing in a direction parallel to a straight line from the center of said magnets to the center of said magnetic region of said levitated element and wherein said first magnetic means and said magnetic element have their opposite magnetic poles adjacent to each other.

12. A levitating system as defined in claim 2 wherein said second magnetic means comprises a second pair of spaced bar magnets with poles facing substantially in the opposite direction as said poles of said first magnetic means.

13. A levitating system as defined in claim 10 wherein said second magnetic means comprises a second pair of spaced bar magnets with poles facing substantially in the opposite direction as said poles of said first magnetic means.

14. A levitating system as defined in claim 11 wherein said second magnetic means comprises a second pair of spaced bar magnets with poles facing substantially in the opposite direction as said poles of said first magnetic means.

15. A levitating system as defined in claim 2 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field, said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

16. A levitating system as defined in claim 4 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

17. A levitating system as defined in claim 6 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

18. A levitating system as defined in claim 7 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

19. A levitating system as defined in claim 8 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

20. A levitating system as defined in claim 9 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

21. A levitating system as defined in claim 10 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

22. A levitating system as defined in claim 11 wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the

region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

23. A levitating system as defined in claim **12** wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

24. A levitating system as defined in claim **13** wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

25. A levitating system as defined in claim **14** wherein said controllable force means comprises an electromagnet formed by two coil sections arranged with a gap therebetween, said gap being symmetrically positioned relative to said stability plane, said gap providing a leakage magnetic field, said leakage magnetic field from said gap having a polarity opposite to the polarity of the magnetic field created by said electromagnet in the region surrounding said electromagnet and wherein said leakage field and said surrounding field substantially cancel each other at said stable position.

26. A levitating system as defined in claim in claim **1** wherein said static magnetic means comprises a main magnet having an annular groove formed in a face thereof facing said levitated element and wherein said main magnet and said magnetic means of said levitated element have their opposite magnetic poles adjacent to each other.

27. A levitating system as defined in claim in claim **3** wherein said static magnetic means comprises a main magnet having an annular groove formed in a face thereof facing said levitated element and wherein said main magnet and said magnetic means of said levitated element have their opposite magnetic poles adjacent to each other.

28. A levitating system as defined in claim **26** wherein said controllable force means comprises an electromagnet substantially positioned in and extending around said annular groove.

29. A levitating system as defined in claim **27** wherein said controllable force means comprises an electromagnet substantially positioned in and extending around said annular groove.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,168,183
APPLICATION NO. : 07/676066
DATED : December 1, 1992
INVENTOR(S) : Lorne A.R. Whitehead

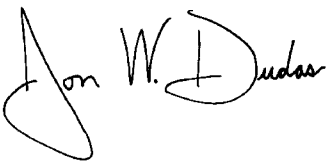
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 12, line 18 claim 1, insert the following:

said static magnet means including fixed magnets arranged at a particular spacing relative to one another in order to generate said magnetic configuration with said magnetic means in the levitated element

Signed and Sealed this

Third Day of June, 2008



JON W. DUDAS
Director of the United States Patent and Trademark Office